Air pollution studies at the Alberta oil sands area

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Abstract

Three intensive studies were made at the Oil Sands area in Alberta to study its meteorology and dispersal and deposition of pollutants. In addition these studies included a program to measure the rate of SO_2 oxidation in the Great Canadian Oil Sands plume.

Measurements procedures and data handling were described. Some interesting results typical of that area were discussed. Areas of uncertainty in the measurements procedure were identified.

Introduction

Industrial plumes disperse and change their chemical composition as they travel in the atmosphere. The mechanisms of dispersion and chemical change within the plume are functions of local meteorological parameters (e.g. wind speed, wind direction and temperature), topography, and the chemical composition of both the plume and the atmosphere. The effects on the air quality of the area are numerous as has been demonstrated in many air pollution studies[1,2,3]. In order to examine the effects of the changes under winter and summer conditions, three field studies were carried out during March 1976, February 1977 and June 1977 in the AOSERP study area.

These studies had the following specific objectives:

(a) To obtain detailed information on wind flow and temperature of the atmospheric boundary layer.

(b) To obtain information on the rise of the GCOS plumes, and on the dispersal and concentration of their particulates.

(c) To examine the air quality of the area and to measure the deposition of heavy metal and sulphur-bearing particles.

(d) To determine the rate of SO_2 oxidation and its photochemical aspects.

As a consequence, the AES experimental program consisted of wind, temperature and humidity measurements as a function of height using balloon-born minisondes and radiosondes tracked by theodolites, and a tethersonde, photography of the GCOS plume, particulate sampling of the plume by LIDAR and aircraft sampling of SO_2, sulfate and sulfuric acid in the plume.

These measurements were supported by stack sampling made by the Great Canadian Oil Sands (GCOS).

The paper describes briefly the measurements procedures. Some interesting results typical of that area are also discussed.

Site and Source Description

In general the AOSERP study area under consideration comprises 31,068 km^2 in Alberta, Canada.

The study region of this program centers on the GCOS and Syncrude plants at about 40 km north of Fort McMurray. Both plants lie west of the Athabasca River (Fig. 1). It should be mentioned here that only the GCOS plant was in operation during the study period. The Syncrude plant was under construction.

The topography around the Athabasca River in that area is slightly variable, ranging from undulating to rolling land.

The Athabasca River flows across this part of the land from south to north. The river valley's elevation is about 230 meters MSL and it has a width of about 1 km at the GCOS plant. The valley slopes rise gradually to an elevation of about 400 meters at 24 km distance to the east and for the same distance

to the west it rises to an elevation of 520 meters.

The GCOS plant is located within the valley, while the Syncrude site is at about 5 km west of the GCOS plant.

The major emission sources in the GCOS plant are three stacks; the Power Plant Stack (A), the Refinery Flare Stack (B) and the incinerator Stack (C). The emissions originate from the consumption of 2×10^6 kg/day of petroleum coke containing 6% sulfur.

The relative locations of these stacks are shown in Fig. 1. The GCOS stack characteristics are given in Table 1. The plant produces about 45,000 bbl/day of synthetic crude oil. The range of the meteorological conditions, prevailed during the study periods, are summarized in Table II.

Experimental

The experimental technique employed in these studies to obtain local plume chemistry, dispersion data and the concurrent meteorological parameters are described in detail elsewhere[1,4,5]. Briefly, measurements of the rise and dispersion of the GCOS plume were obtained through the use of photography and a mobile laser radar. The plume chemistry was done by aircraft sampling of SO_2 across the plume.

In photographing the plume a specially designed set up camera was used. Photographs of the plume were taken every 15 seconds for about 10 minutes period. The time-mean path of the plume rise was then determined by superimposing several photographs and tracing the plume outlines or by using time-average photographs of the plume.

There are some sources of error in applying the above mentioned technique due to fluctuations in wind direction, distortion and visibility of the plume.

Changes in the wind direction in the boundary layer may average about 10^o and may be as high as 80^o in 30 minutes period. Halitsky[6] provided a detailed discussion of the errors in determining the plume rise applying the photographic technique. If the change in the wind direction has not been taken into consideration, it is estimated that 50% error arises in the plume rise for a 10^o wind direction change.

In the plume rise measurements it is assumed that the concentrations at the edge of the plume is equal to 10% of that of the centerline. This assumption is a rough approximation but has the advantage of common usage with good results.

The LIDAR unit was self contained in a standard 3/4 ton van. It operates a 1.0 J ruby laser with a six second repetition rate. The transceiver assembly is rotatable through 360^o of azimuth and 180^o of elevation. The unit was operated only in the last field study of June 1977. The data were taken with the LIDAR Fortran routine, and were stored on floppy diskette on a shot by shot basis. These shots were combined by the statistics routine (STAT) to form a single "scan" through the plume. A series of "scans" over the period of approximately 1/2 hour formed a type of average plume profile. These profiles represented a statistical ensembles. Each scan of the plume was analyzed for the horizontal and vertical

moments of the concentration distribution and the relevant dispersion parameters were obtained.

Over 750 laser firings during the field project yielded 58 individual samples or scans which were combined to obtain 11 "half-hour" averages and two hourly averages.

It must be noted that only under exceptional circumstances will the plume be normal to the scanning plane. In those cases where it is not at right angles, the standard deviation must be compressed by the cosine of the angle between the scanning plane and the normal to the plume bearing. There is additional error introduced in doing this since downwind dispersion becomes folded into the horizontal measurement. It has been shown theoretically for Gaussian plumes, however, that the error introduced by this procedure into the calculated σ_y is less than 10% as long as the angle defined above is less than 80^0 for stable conditions and 50^0 for unstable conditions.

A Bell Jet Ranger helicopter was used in the survey of dispersion and oxidation of sulfur dioxide in the plume of the GCOS power plant. It was instrumented with a Sign X continuous sulfur dioxide analyser to determine dispersion rates, and two parallel filter packs to obtain sulfur dioxide oxidation data. The Sign X has a sampling rate of 2ℓ min^{-1}. It had a "dead time" (time before a step change in concentration at the inlet is sensed by the instrument) of about 1.5 sec and a time constant of 3.3 sec.

The filter pack method has been described in detail in another report[4]. Very briefly, the pack consisted of a modified Swinnex 47 mm filter holder which contained three filters - first, either a Whatman 40 (cellulose), Mitex (teflon) or Delbag (polystyrene) filter to collect particulate matter; and then, separated from the particulate filter, two chemically-impregnated filters, placed back-to-back, to trap the SO_2 in the same plume sample. Whatman 41 cellulose filters, treated with an aqueous solution of glycerol and potassium carbonate, were found to give a very high trapping efficiency.

An attempt was made to sample the plume at two or three locations downwind of the chimney - one within about 1 km, another as far as possible (usually approximately 30 km), and the third at an intermediate location.

All chemical analyses were done at the Atmospheric Environment Service Chemistry division's laboratory, while the neutron activation analyses were carried out at the University of Toronto.

An intercomparison of the amounts of particulate sulfate and SO_2 collected on parallel filter packs indicated that the reproducibility of the filter pack method is good for SO_2 (better than 15%), but much poorer for the particulate sulfate (about 30% or worse). This is probably due to difficulties associated with the sampling of particulate matter rather than chemical analysis problems, and introduces a fairly large scatter in the experimental data.

Experimental Results and Discussion

There are numerous formulas for modeling the rise of a buoyant plume[8].

In order to model the rise of a buoyant stack plume, these widely used formulas require re-evaluation. In this study the most commonly used formulas, namely Briggs [8,9,10], TVA [10,12], Holland [13], CONCAWE [14], Moses and Carson [15] were selected to examine their predictive capability in determining plume rise. This was done by comparing the observed plume rise with the predictive value; samples of these comparisons are shown in Figures 2 and 3.

It has been noted that by the scatter of the points in the figures that none of the models is a good predictor for the measured values. Briggs, TVA 1972, and Moses and Carson's formulas underpredict the rise of the plume, which will lead to over-estimation of the maximum ground-level pollutant concentration. The reverse is true with the remaining formulas.

The predictive capability of these formulas depend on the wind speed. The mean values of the ratio of the observed plume rise to the predicted value of the plume rise for different ranges of wind speed were calculated. With all the formulas except Briggs', the fit becomes steadily worse with increase in the wind speed. By comparison, Briggs' model appears to perform best.

In addition to the determination of the plume rise, some interesting observations on the behaviour of the plume were recorded. On some occasions during the morning, the plumes from the GCOS plant were trapped under an inversion layer and fanned. This limited their rise to the inversion base height, and the plume outlines appeared as a thin ribbon. On other occasions, some of the plumes were able to penetrate the inversion layer and continue to rise till they lost their buoyancy and momentum.

The estimated values of σ_y and σ_z were grouped according to stability categories determined by applying the algorithm of Turner [16] to hourly observations from Fort McMurray Airport (40 km south of the AOSERP study area). For comparison purposes and to provide a frame work for discussion, the observed σ_y and σ_z were compared with the well known Pasquill-Gifford dispersion curves as given by Turner[16].

It was noted that there is no apparent relationship between the observed and predicted values of both σ_y and σ_z. Both estimated values of σ_y and σ_z are larger than would be predicted close to the source. At a larger downwind distance ($x > 1$ km for σ_y and $x > 200$m for σ_z) most of the observed values of σ_y and σ_z compare with Pasquill-Gifford values for unstable and neutral conditions.

The disagreement between the measured dispersion parameters is not surprising. The Pasquill-Gifford curves are designed to describe dispersion from a ground-level source, with a surface roughness of a few cms and a downwind distance of 800 m and a non-buoyant source.

In order to improve the predictive capability in determining the dispersion coefficients many workers developed improved models for larger applications than the one discussed above. A detailed discussion of these different models is given by Pasquill [17] and summarized by Gifford [18].

One of the models was developed by Smith [19] (ASME model). The model was based on measurements of concentration patterns of plumes from elevated sources. The measurements were supported by related values of meteorological parameters and it is simple to implement.

The LIDAR measurements of σ's were compared with the ASME model in Figures 4 and 5. The neutral cases are in fair agreement with ASME predictions. The stable cases, however, show disagreement with ASME predictions in particular for in the case of σ_z.

Several effects, not accounted for in simple Gaussian formulations of dispersion, cause this large discrepency in dispersion in stable regimes. Turbulent motion of a buoyant plume rather than atmospheric dispersion accounts primarily for its growth near the stack.

With regard to the SO_2 oxidation rate of the plume in the AOSERP area it was found that during February the oxidation rate was low. It scattered about zero for a certain plume age interval (12-68 min). During June, the flights carried out prior to about 0700 hrs. also show very low SO_2 oxidation rate, most of the observed values being well below 0.5% hr^{-1}. Later in the day the rate increased to values greater than 1% hr^{-1} typically, about 2-3% hr^{-1}. An ozone concentration change was observed during several of these latter flights. This suggests photochemical processes play an important role in SO_2 oxidation in for the GCOS plant.

Concluding Remarks

It is apparent from the observations presented, that there is no one simple universal formula that will describe the plume rise in the AOSERP area. It is believed that several aspects of the plume behaviour (e.g., looping and shear) should be taken into account before a satisfactory formula can be derived.

In analysing plume dispersion information, it is apparent that the dispersion along the vertical is not well represented by Pasquill-Gifford curves. However, information from the LIDAR project indicated that the dispersion of the GCOS plume is reasonably well represented by the ASME model for neutral atmospheric conditions. However, as was seen in previous studies, dispersion in stable atmospheric conditions is larger than would be predicted by tabulated Gaussian dispersion coefficients. It is believed that this increased dispersion is predominantly due to the dynamic behaviour of the buoyant plume near the stack. The need is seen for plume dispersion models to incorporate these dynamical effects as well as wind shear and looping in the prediction of dispersion in this region.

The LIDAR and the camera have been shown to be extremely useful tools for the measurement of plume rise and dispersion in the AOSERP study area, especially in light of the constrained road network for other types of sampling (e.g., COSPEC). LIDAR, however, is a technique which is still in research rather than operational stage. It requires a fair degree of sophistication in its operation and a high degree in interpretation of the data.

During February the SO_2 oxidation rate in the GCOS power plant is low. Early morning in June the rate is also low, typically less than 0.5% hr^{-1}. Later in the day, under the influence of intense atmospheric turbulence, the conversion rate can increase to values as great as 3% h^{-1}.

One of the main objectives of the AOSERP Air System is to predict the impact of air pollution on the Oil Sands area by means of modelling. The use of such models will require detailed information on the wind flow and temperature structure of the planetary boundary layer of that area, on the rise and dispersal of industrial plumes, on the chemical transformation and deposition of pollutants

and on the background and ambient air quality.

The AES three field studies supplied the above needed information.

Acknowledgement

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TABLE 1

Characteristics of the GCOS Stacks

	Stack A	Stack B	Stack C
Height above ground (m)	106	99	107
Inside Diameter (m)	5.89	1.1	1.8
Average Exit Velocity ($m\ s^{-1}$) (annual)	17.5	5	17
Stack Gas Temperature (C)	272	600	610
SO_2 Emission Rate ($Kg\ s^{-1}$)	2.6	0.1	0.27
Particulates ($Kg\ s^{-1}$)	0.37	0	0

TABLE II

Meteorological Conditions at the Plume Level
During the Study Period

Date	Mean Wind Speed ($m\ sec^{-1}$)	Average Air Temperature (C)	Potential Temperature Gradient (C/M)
March 76	1.5 to 13.7	-24 to 4.8	- .03 to .03
February 77	0.9 to 7.2	-21 to 8	- .01 to .02
June 77	0.5 to 11.0	9 to 26	- .01 to .03

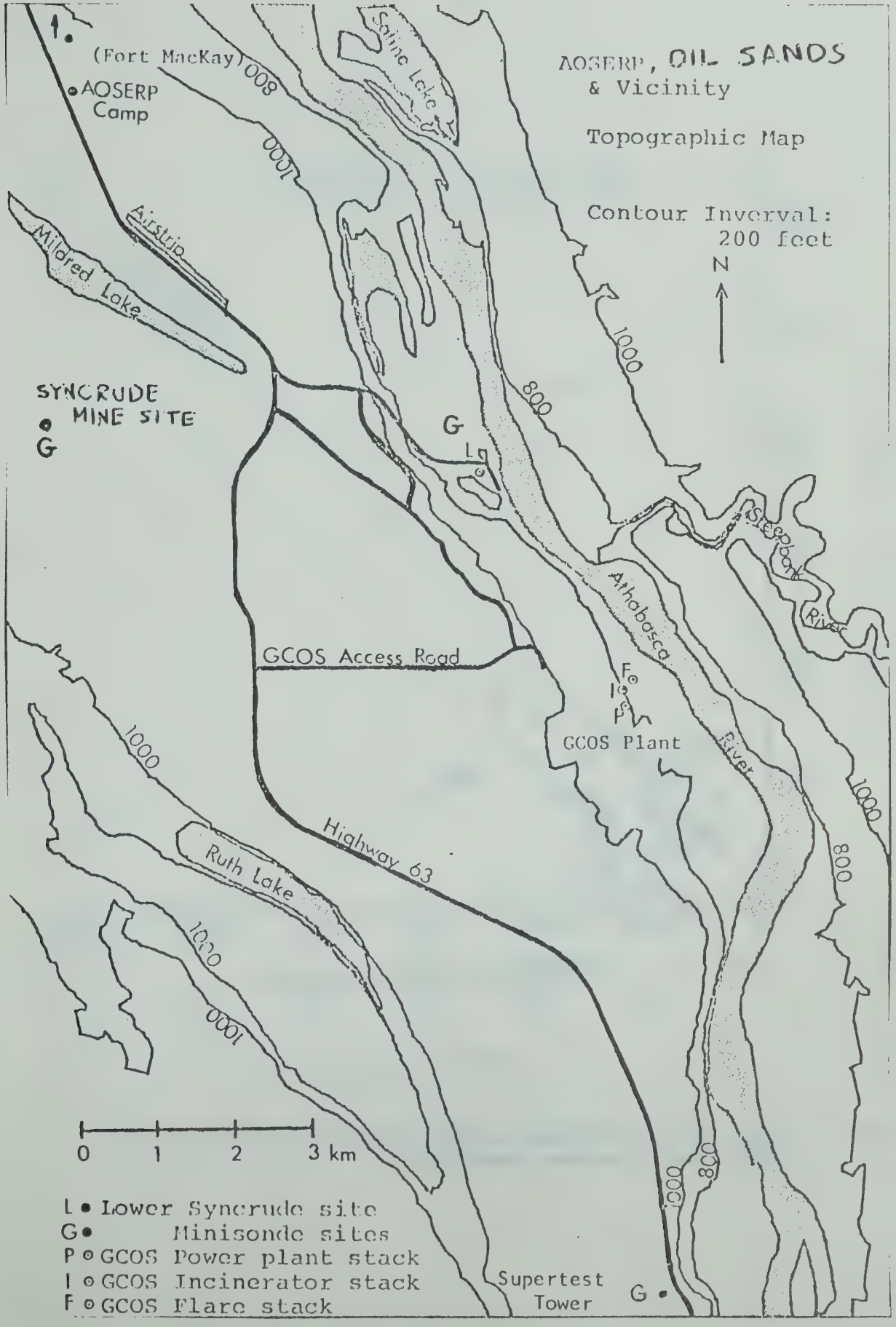

Fig. 1 Map of the AOSERP area, showing the location of the GCOS plant and minisonde sites.

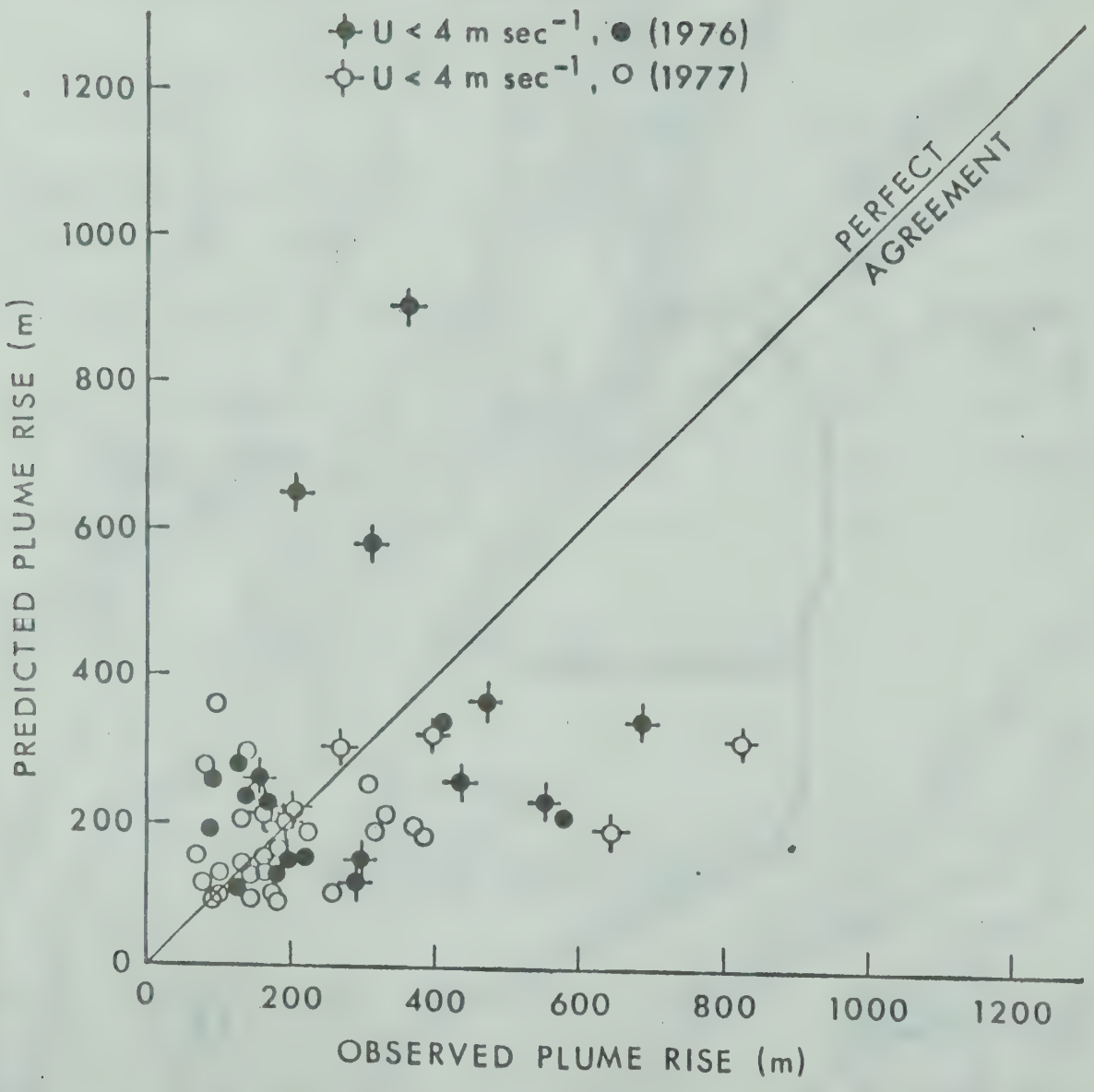

Fig. 2 Comparison of predicted versus observed plume rise using Briggs' model (winter conditions).

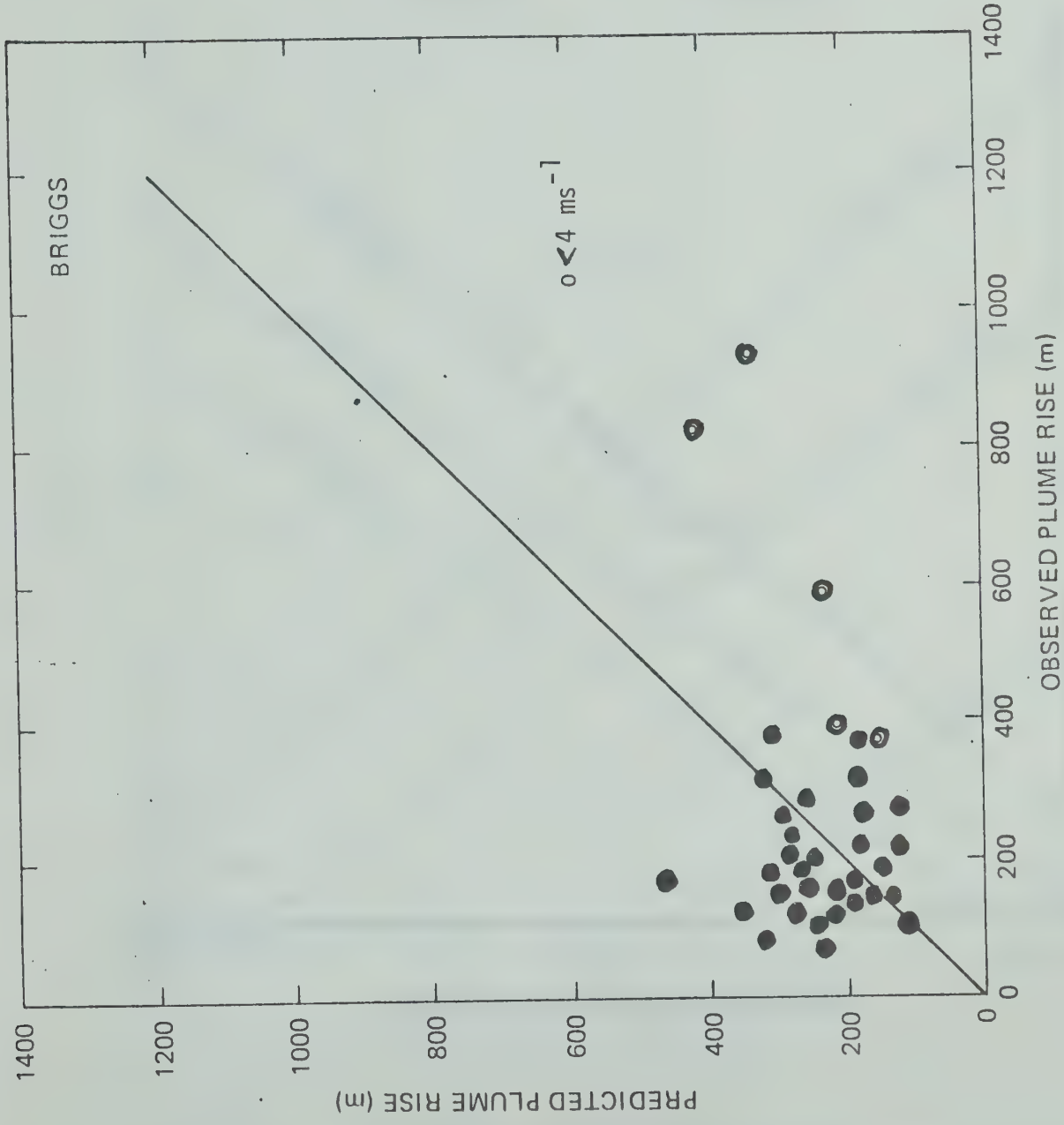

Fig. 3 Comparison of predicted versus observed plume rise using Briggs' model (summer conditions).

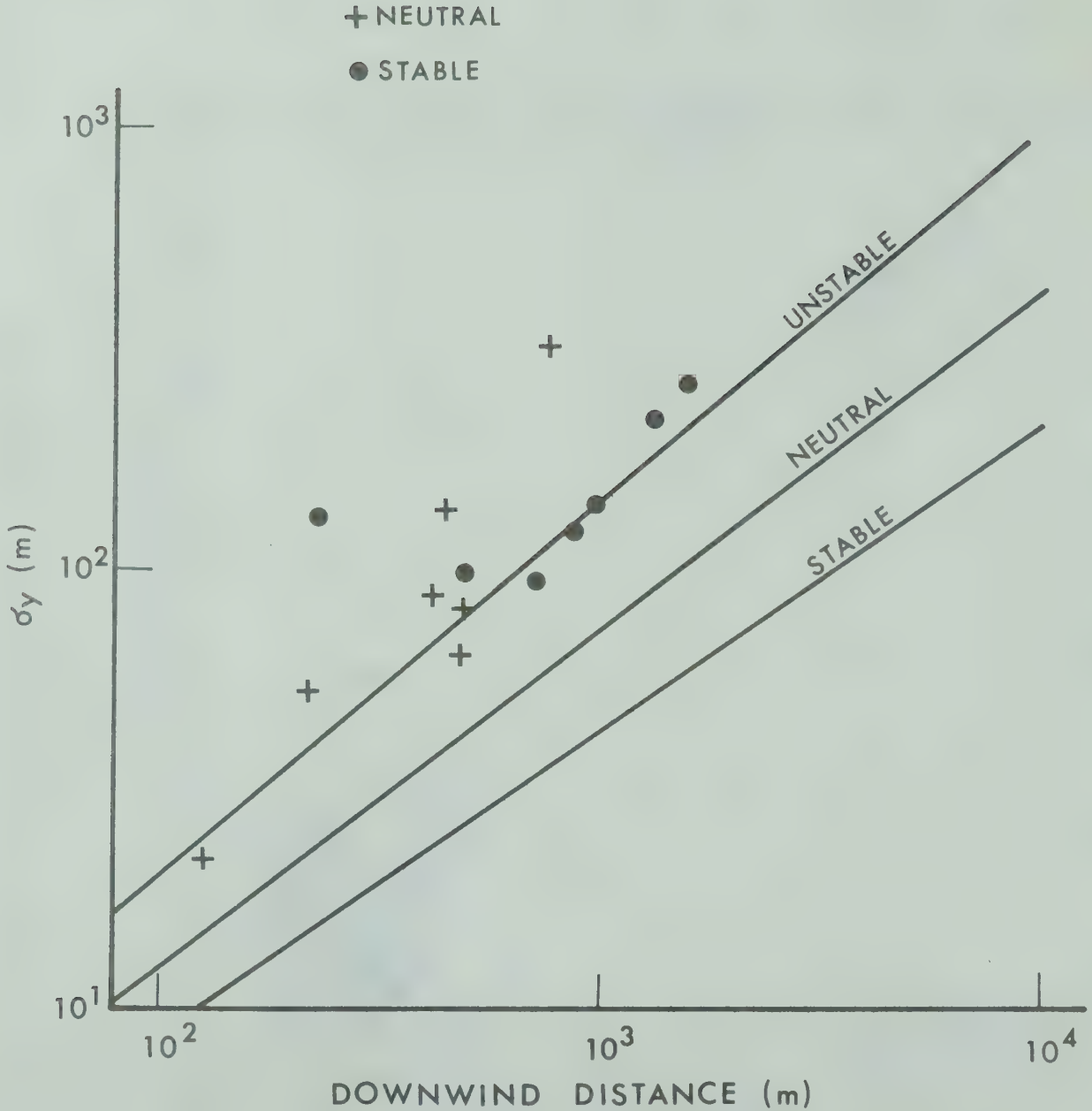

Fig. 4 Comparison of measured σ_y versus ASME curves.

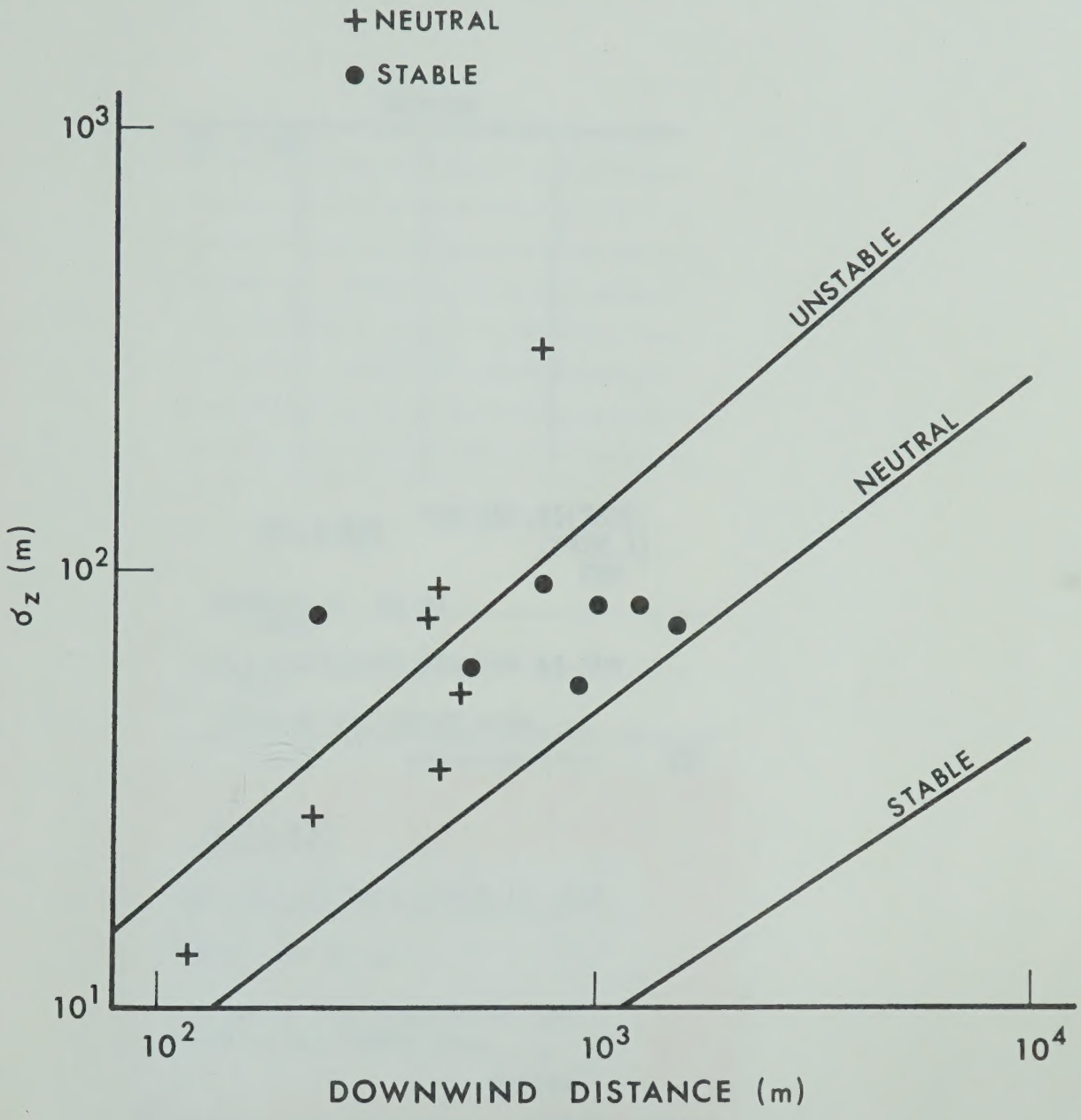

Fig. 5 Comparison of measured σ_z versus ASME curves.